The Effects of Sound on the Marine Environment

Michael B. Porter
Heat, Light, and Sound Research, Inc.
3366 N. Torrey Pines Court, Suite 310
La Jolla, CA 92037
phone: (858) 457-0800 fax: (858) 228-1734 email: mikeporter@hlsresearch.com

Award Number: N00014-09-C-0412
http://www.hlsresearch.com/

LONG-TERM GOALS

To develop novel techniques to predict the impact of sound on the marine environment and use natural sound sources (such as whale calls) to observe non-invasively both animal behavior and the marine environment.

OBJECTIVES

Concern has increased about the role of man-made noise in the marine environment. To address this, ONR has supported the development of the Effects of Sound on the Marine Environment (ESME) workbench. The initial Graphical User Interface was developed by NRL using Matlab with calls to FORTRAN implementations of acoustic propagation models. The acoustic modeling tools are mostly drawn from ONR's Ocean Acoustic Library (http://oalib.hlsresearch.com/), which provides the latest open source R&D models.

ESME has emerged as the navy standard for such modeling. Its *open source* and *peer-reviewed* approach are seen as very favorable. In addition, ESME has emphasized the need for the highest-quality results taking advantage of state-of-the-art propagation models and marine-mammal movement models. The latter led to an 'animat' construction that simulates the motion of individual marine mammals as they move through the sound field, and respond with aversion behaviors.

The Navy has adopted ESME now as an operational tool. Much work is needed to rapidly bring it to that level, which is the key goal of the work reported here.

APPROACH

Task I: Exercise-and-Shipping Noise Simulator (Chris de Moustier)
We are developing a shipping noise simulator that incorporates temporal, spatial, and frequency-dependent variables to be used as a predictive ESME tool or a Navy exercise-planning tool. Our approach involves pre-computing frequency and range-dependent transmission losses from a grid of virtual sources (0 dB source level) using coherent BELLHOP runs on a specified number of radial lines. Each radial line samples the bathymetry along its bearing out to a given maximum range.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2010**	2. REPORT TYPE	3. DATES COVERED **00-00-2010 to 00-00-2010**
4. TITLE AND SUBTITLE **The Effects of Sound on the Marine Environment**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Heat, Light, and Sound Research, Inc,3366 N. Torrey Pines Court, Suite 310,La Jolla,CA,92037**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**12**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

For acoustic frequencies between 50 Hz and 500 Hz in the shipping noise band (10 Hz – 500 Hz), a shipping "noisescape" is estimated by assigning a source spectral density level (dB re 1 μPa^2/Hz) and a shipping density (number of ships per unit area per unit time) to the various grid nodes. Such density values are obtained directly from ships carrying an Automatic Identification System (AIS) that transmit information such as ship type, position, heading, and speed. They can be obtained also from compiled statistics of AIS data (e.g. number of transits per year in an area).

We use the same gridding approach to predict wind-generated noise levels based on maps of average wind speeds in an area for a given epoch, or on maps of forecast wind speeds in preparation for an exercise.

Task II: Nonlinear Explosives Model (John Peterson, Laurel Henderson, Ahmad Abawi)
We have investigated two options: 1) A nonlinear version of BELLHOP, and 2) An open-source implementation of a nonlinear PE.

Task III: Glinting Effects (Ahmad Abawi and Martin Siderius)
By 'glinting' we mean the high intensity sound levels due to focusing by ocean surface waves. For the ESME Workbench we use a virtual source approach to examine whether simple corrections can be made to approximate the full 3D effects of surface waves in a 2D Gaussian beam code (BELLHOP).

Task IV: BELLHOP manual.
BELLHOP is the Open Source ray/beam tracing model used pre-dominantly for the propagation modeling in the ESME package. It is also widely used in the marine mammal community. The brief online help files are normally sufficient for an experienced acoustic modeler to use it. However, there have been many requests for a more complete manual.

WORK COMPLETED

Task I: Exercise-and-Shipping Noise Simulator (Chris de Moustier)
We have implemented a simulator in MATLAB. The inputs include the bathymetry and the oceanography for the area of interest. This simulator can handle several thousand virtual ship locations. Specific shipping lanes with user selectable widths can be used to distribute ships in time and space and estimate the resulting noise levels at specific frequencies.

Effects of the bathymetry on the noise estimates have been verified by comparison with a flat bottom.

We have also documented a procedure to compute shipping-density estimates (number of ships per km^2 per second) based on available ship-traffic statistics.

Task II: Nonlinear Explosives Model (John Peterson, Laurel Henderson, Ahmad Abawi)
We focused initially on the Nonlinear PE developed by Ed McDonald at NRL. To ensure a fully open version for ESME distribution, we implemented a preliminary 1D, then 2D version in Matlab based on the published algorithm. Separately, we revisited the earlier linear approach implemented in ESME in which a simple formula for the explosive timeseries was convolved with the BELLHOP impulse response. This latter approach neglects the nonlinear effects associated with finite amplitude sources. To improve that further we modified the convolution to use an explosive timeseries satisfying experimentally derived similitude relations that govern the amplitude of the shock and its decay constant as a function of distance from the source.

Task III: Glinting Effects (Ahmad Abawi and Martin Siderius)
A metric based on the ``scintillation index" was implemented to provided a quantitative measure of the importance of the glinting. In addition, a formal theoretical analysis was completed to give a qualitative sense of the strength of the glinting as a function of frequency, geometry of the source (line or point), and curvature of the ocean surface. The method was benchmarked against an independent solution, and results were documented in a journal article submitted to the J. Acoustical Society of America.

Task IV: BELLHOP manual
A first draft of the BELLHOP manual was completed and made available on the ONR Ocean Acoustics Library. Several revisions were also completed.

RESULTS

Task I: Exercise-and-Shipping Noise Simulator (Chris de Moustier)
We have tested this simulator at 50, 100, 200, and 400 Hz in the Stellwagen Bank Sanctuary (centered on 42.5º N/ 70.2º W) (Fig. 1). The effects of the bathymetry on the received noise levels from a single ship are shown in Fig. 2. Computations were done also on a regular grid of 836 such sources 2.5 km apart in latitude and longitude. At first, we used shipping density statistics from 2006 (Hatch et al, Environmental Management, 42, 735-752, 2008), and assumed a uniform distribution of ships throughout the area. The resulting noise spectral density levels (Fig. 3) are 20-30 dB lower than the generic values expected at these frequencies (e.g. Fig. A.2, Appendix A, in R. J. Urick, "Ambient Noise in the Sea", Naval Sea Systems Command, 1984). Closer agreement is obtained when ships are distributed uniformly inside the five major shipping lanes of the Boston, MA, Ship-Traffic Separation Scheme. Tests with shipping lane widths of 3 to 6 km yield shipping noise spectral levels that are within a few dB of the generic values at each frequency (Fig. 4). The results show also a strong masking effect of the bathymetry on the noise levels, with some evidence of frequency dependence.

The main result of this work is the ability to run realistic simulations and predict the contribution of shipping noise to the overall oceanic noise budget at a specific location using local bathymetry and environmental conditions, plus real-time AIS data or complied shipping statistics.

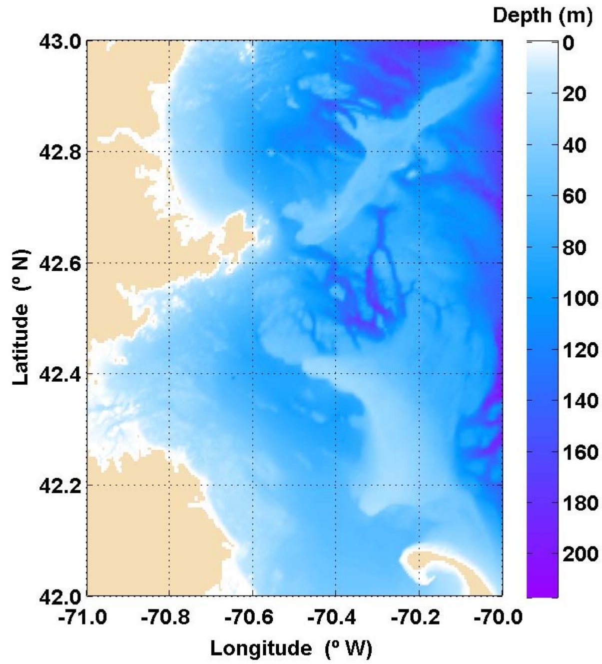


Figure 1. Bathymetry of the Stellwagen Bank Sanctuary. Uniform grid with 0.16 km^2 cells (data source: NOAA's National Geophysical Data Center, US Coastal Relief Model grids).

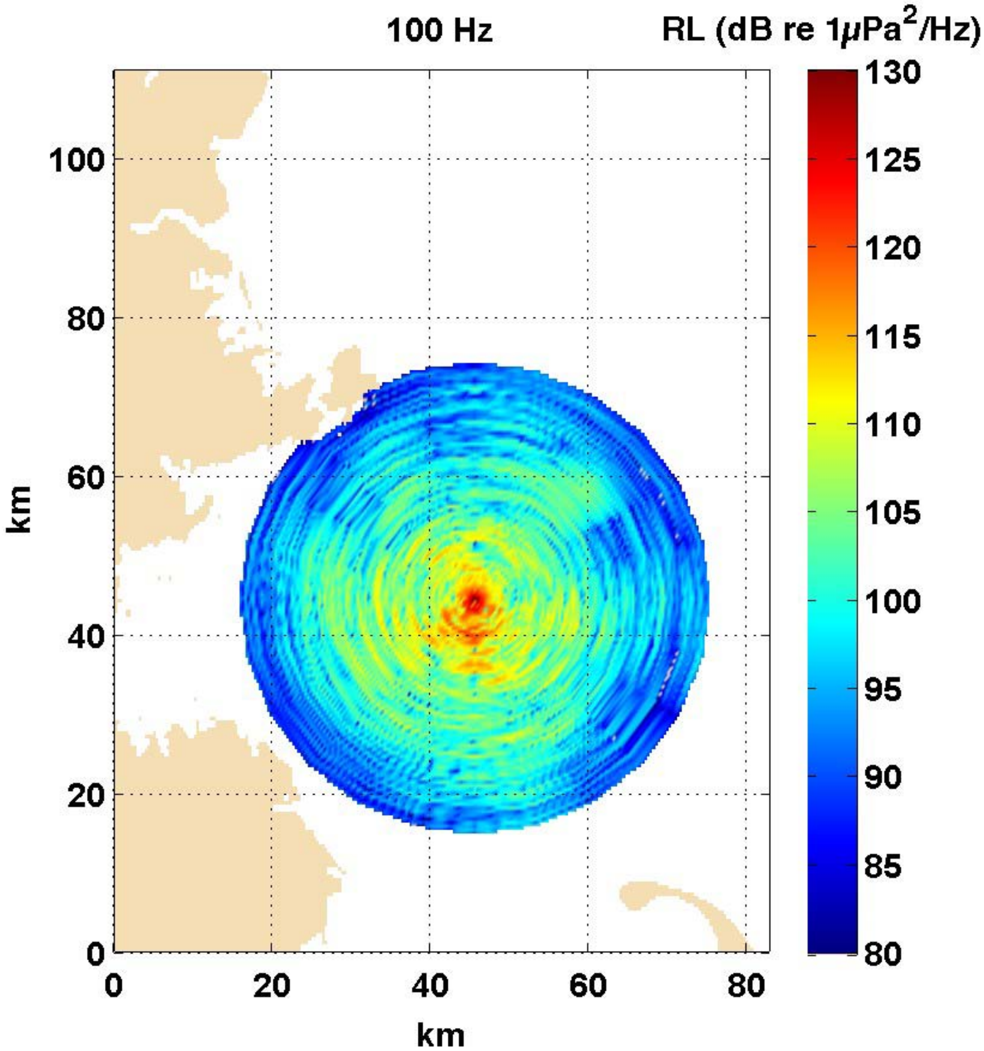


Figure 2. Modeled received spectral density level (dB re 1 μPa^2/ Hz at 100 Hz) at 10 m depth out to 30 km range (radius of disk in image). An omni-directional source is at the center of the disk, at 7.5 m depth with a source spectral density level of 167.5 dB re 1 μPa^2/ Hz at 100 Hz. The received levels are computed on 24 range dependent radials. The anisotropy of the received levels is due to the bathymetry. Map origin at (42º N/ 71º W).

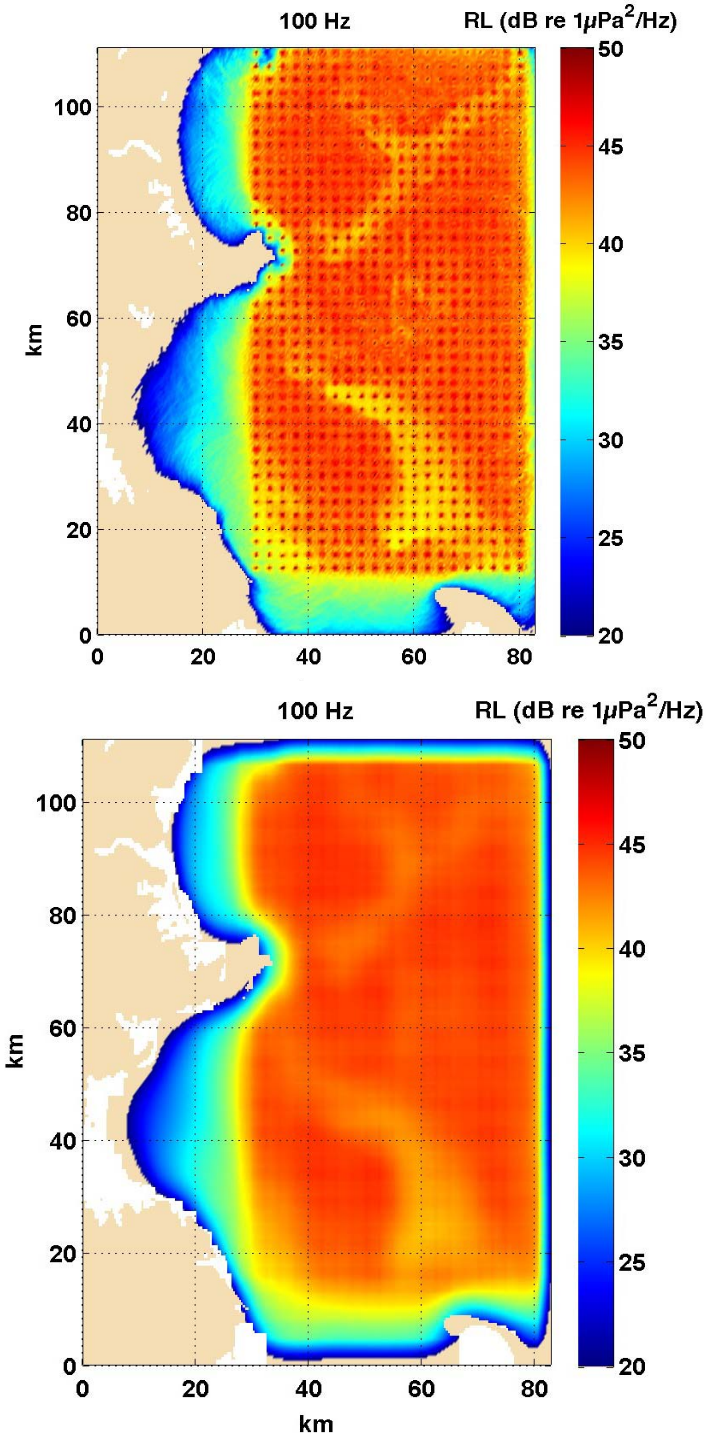
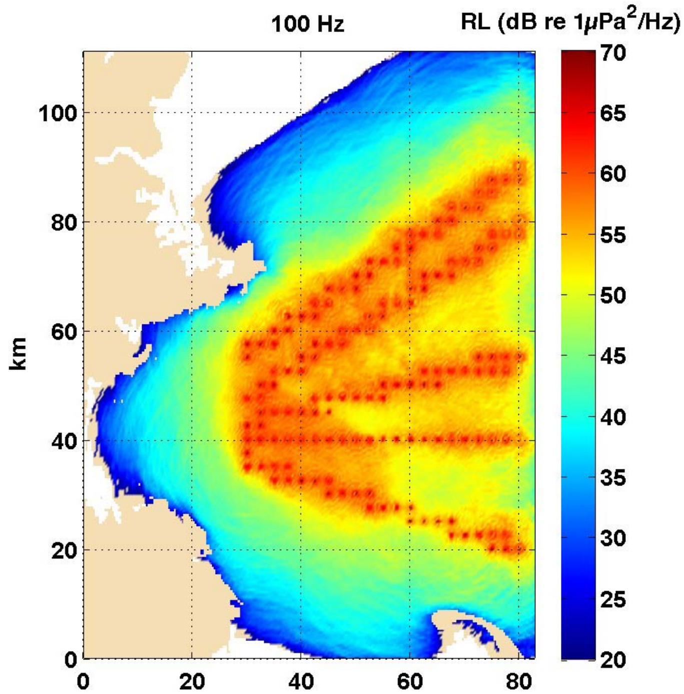


Figure 3. Noisescape at 10 m depth for 836 virtual sources spaced 2.5 km apart in latitude and longitude. Each source has the same characteristics at that shown in Fig. 2. A uniform shipping density is assumed. The received spectral density level is about 5 dB higher in the basins than on the bathymetric ridges: a) Raw, b) smoothed with a 2D rectangular filter roughly 7 km on a side. Map origin at (42º N/ 71º W).



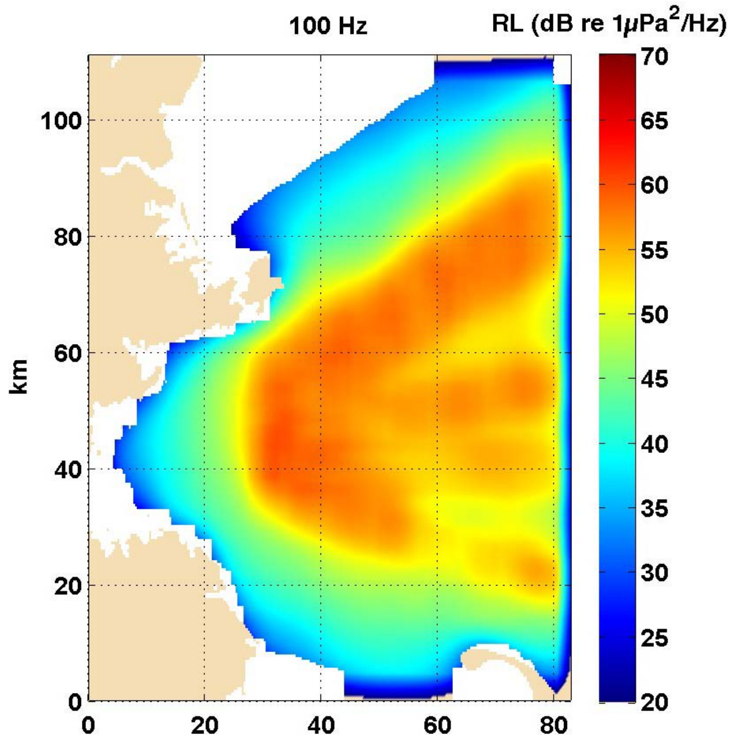


Figure 4. Noisescape resulting from the 5 main shipping lanes into Boston Harbor. Each lane is 3 km wide. Received spectral density level at 10 m depth for sources with identical characteristics as those of the source in Fig. 2: a) raw, b) smoothed with a 2D rectangular filter roughly 7 km on a side. Map origin at (42º N/ 71º W).

Task II: Nonlinear Explosives Model (John Peterson, Laurel Henderson, Ahmad Abawi)
Because of space limitations we will present examples just for the nonlinear version of BELLHOP, rather that the Nonlinear PE. The scenario selected was one that had previously been used by NUWC for testing the in-house version of the "One Navy Model''. Traditional units were used to facilitate comparison to the Navy models. The sound speed profile for the test case is shown in Fig. 5 corresponding to a site in the Southern California Offshore Range.

The result of the nonlinear BELLHOP simulation is shown in Fig. 6 for a 300 lb. charge detonated at a depth of 2500 ft. The receiver is at a range of 1 n. mi. and a depth of about 1000 ft. We see the characteristic shape of the explosive waveform with a sudden rise followed by a more gradual decay in pressure. The shape of the waveform matches fairly precisely the results of a separate CASS/GRAB simulation done at NUWC. REFMS has been selected as the standard for use in the operational navy model. Full REFMS results are not available; however, the 3 models all yield a peak pressure value of about 28 psi.

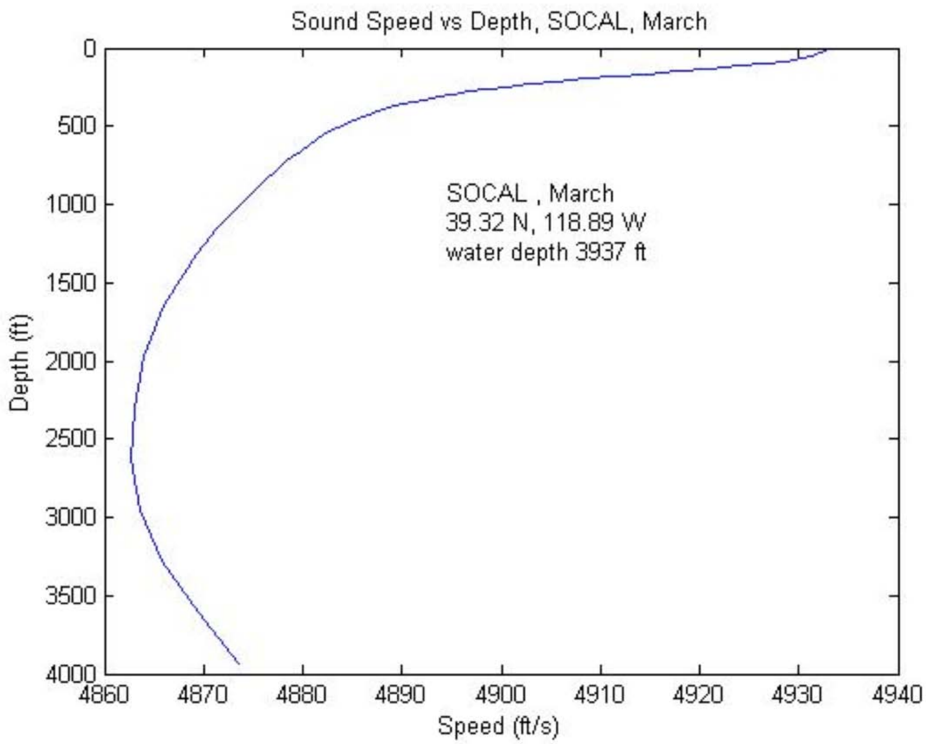


Figure 5. Soundspeed profile for the Southern California test case.

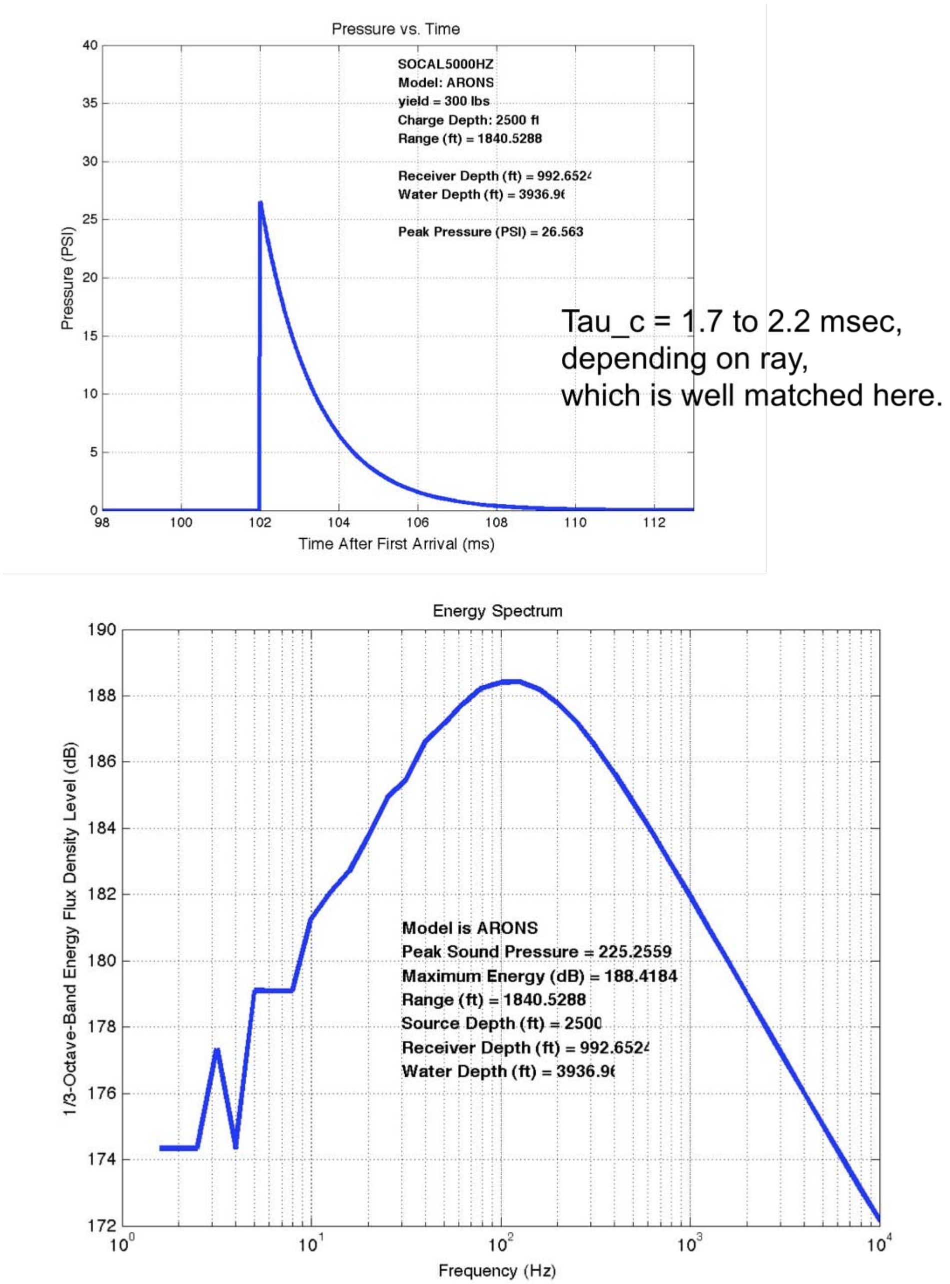


Figure 6. Model results using nonlinear BELLHOP for a 300 lb. explosive: a) received timeseries, b) Energy Flux Density Level in 1/3-octave bands.

Task III: Glinting Effects (Ahmad Abawi)
We have developed a virtual source technique to provide an exact solution for scattering of a plane wave from a pressure-release, periodic surface. In this approach, we use a truncated sum formula, which provides the solution to the scattering problem from an infinitely long surface using a finite number of virtual sources. The periodic nature of the surface causes the incident field to be scattered exactly the same way from points separated by a multiple of surface wavelength. When the path

length difference between the incident and scattered waves is a multiple of the incident wavelength, they interfere constructively, which results in discrete scattering directions described by the grating formula, shown in Fig. 7. An exact solution of this problem guarantees the conservation of energy: This implies that the sum of the intensity scattered in the discrete directions is equal to the intensity of the incident field.

Here we have applied this technique to compute scattering of a plane wave from a pressure-release sinusoidal surface and compared the solution to that obtained using the integral equation technique.

In Fig. 8, we present results for the case when λ=0.25Λ, where λ is the acoustic wavelength and Λ is the surface wavelength. In this case, there are eight propagating modes: l=-7, -6, -5, -4, -3, -2, -1, 0 for an incident angle of 30 degrees, l=-6, -5, -4, -3, -2, -1, 0, 1 for incident angles of 45 and 60 degrees and l=-5, -4, -3, -2, -1, 0, 1, 2 for an incident angle of 75 degrees. The contribution from off-specular angles start when H/Λ is non-zero, where H is the surface height.. However, conservation of energy is satisfied for all values of H/Λ. These results show that the virtual source solution produces identical results to those obtained from the integral equation solution for all propagating modes and a wide range of incident angles.

$$\cos\theta_l = \cos\theta_0 + \frac{\lambda}{\Lambda} l$$

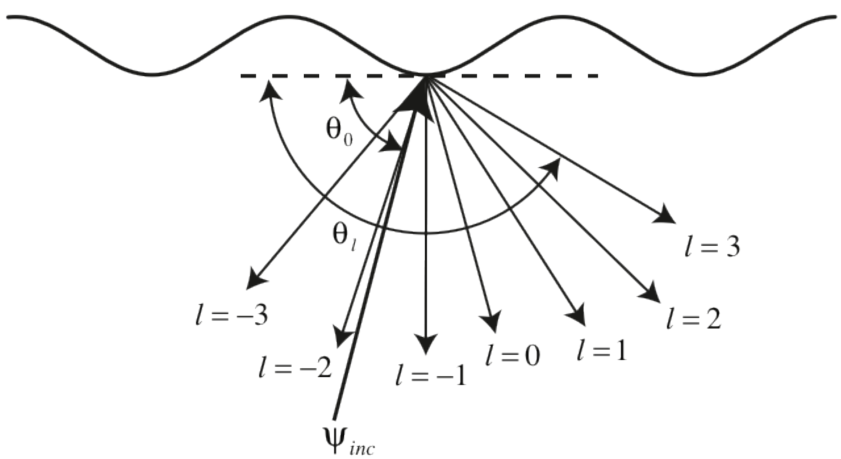


Figure 7. Scattering from a sinusoidal surface showing the angle of the incident planewave and the scattered energy, which propagates at discrete angles according to the grating formula.

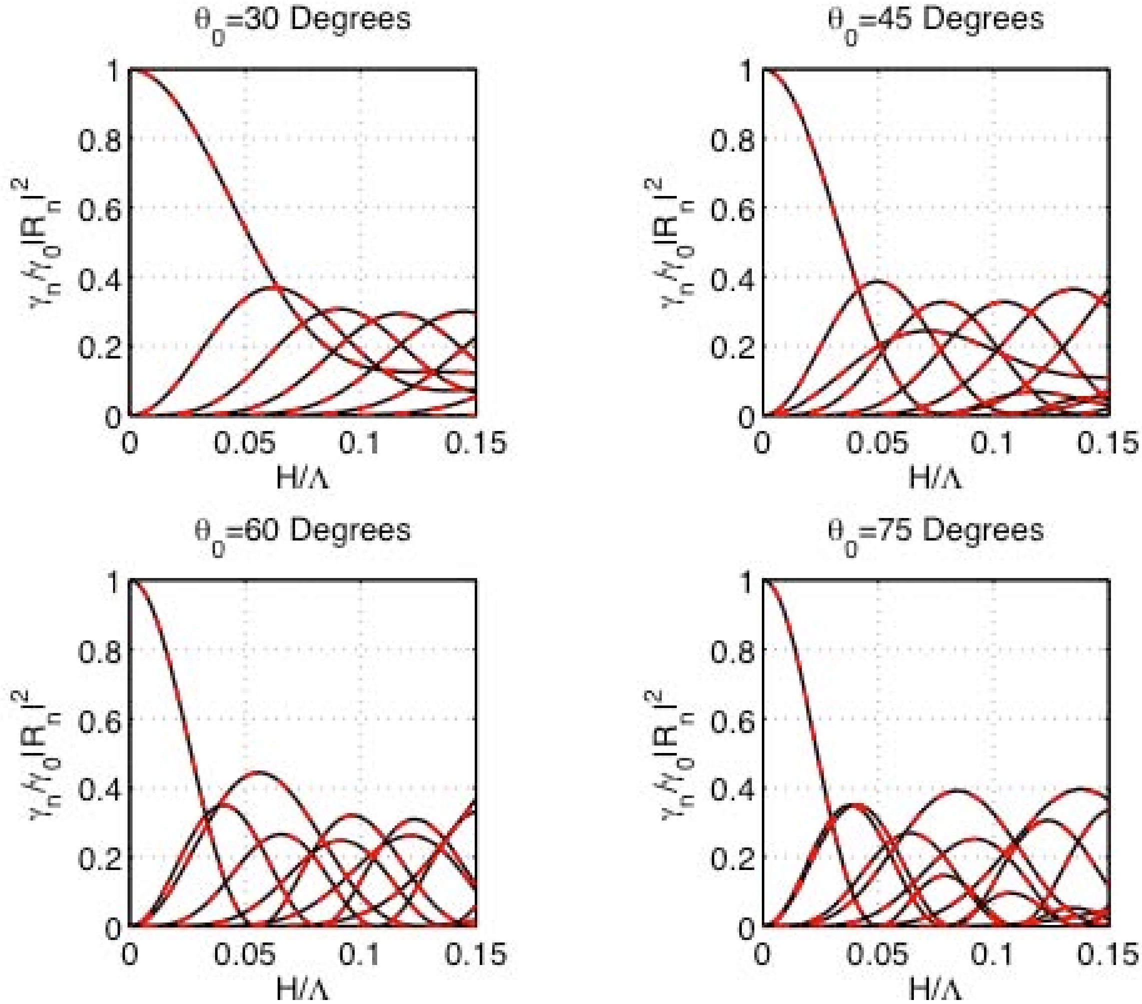


Figure 8. Comparison between the integral equation solution (solid black lines) and the virtual source solution (red dashed lines) of scattering of a plane wave from a sinusoidal surface as function of the ratio of surface height to surface wavelength. The wavelength of the incident plane wave is a quarter of the surface wavelength, resulting in eight propagating modes: l=-7, -6, -5, -4, -3, -2, -1, 0 for an incident angle of 30 degrees, l=-6, -5, -4, -3, -2, -1, 0, 1 for incident angles of 45 and 60 degrees and l=-5, -4, -3, -2, -1, 0, 1, 2 for an incident angle of 75 degrees. The curves that have values of one at $H/\Lambda=0$ correspond to the mode l=0. The other modes have not been labeled. Note that the off-specular modes begin to contribute to the total scattered energy as the surface roughness increases; and at any surface roughness the sum of the energies of all the propagating modes is unity.

IMPACT/APPLICATIONS

The Navy has an urgent need for a standardized software package for modeling the impact of sound on the marine environment. Several tools have been developed and are in use; however, only ESME has been developed as an open source and peer reviewed package.

RELATED PROJECTS

The propagation models used in ESME have been largely supported by the ONR Ocean Acoustics program.